Friction-Stir Processing of a High-Damping Mn-Cu Alloy used for Marine Propellers

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Abstract

Mn-Cu alloys are used for specialised applications, such as marine propellers, where high noise-damping characteristics are required. These alloys tend to have more severe shrinkage porosity than conventional propeller alloys, and the corrosion resistance (including stress-corrosion and corrosion-fatigue resistance) of the alloys is not as high as desirable. Friction-stir processing (FSP) trials on one such alloy (tradename Sonoston) have shown that near-surface porosity can be eliminated and that the coarse, as-cast microstructure can be significantly refined. The corrosion resistance of processed material is substantially improved provided a heat treatment to relieve residual stress is carried out after FSP.

Introduction

Friction-stir processing (FSP) has considerable potential for improving mechanical properties and corrosion resistance of materials by refining microstructures and eliminating any defects in near-surface regions [1]. During FSP, a rapidly rotating tool, comprising a profiled pin and larger-diameter shoulder, is plunged into the material and then traversed across the surface. Frictional heating and extreme deformation occurs, and plasticised material (constrained by the shoulder) flows around the pin and is consolidated behind it. FSP is essentially similar to friction-stir welding (FSW) except that the aim is to produce a thermo-mechanically worked, refined microstructure rather than to join materials. FSP can be applied to local areas of components where enhanced properties are required, so that there is potential for reducing overall product costs and for increasing design flexibility.

FSP and FSW have mainly been applied to aluminium alloys (especially 7xxx series alloys which cannot be fusion welded), but there is increasing effort to apply the technologies to other materials [2,3]. In the present work, FSP has been applied to a Mn-Cu alloy (‘Sonoston’) used especially for marine propellers where high noise-damping characteristics are required [4]. Sonoston is more difficult to cast, and tends to have more severe shrinkage porosity, than conventional propeller alloys [5,6]. Large, slowly cooled Sonoston castings have a coarse microstructure characterised by Mn-rich regions with a dendritic or Widmanstätten morphology. The Mn-rich regions are prone to selective corrosion (de-alloying) in seawater, and the corrosion-fatigue and SCC resistance of Sonoston are not as high as desirable due to cracks formed in the brittle, de-alloyed areas [6].

The main aim of the present work was to determine if FSP could ‘heal’ casting porosity in near-surface regions and refine microstructures to improve resistance to corrosion, SCC, and corrosion-fatigue. This work might lead to a better understanding of FSP since, as far as the authors are aware, FSP and FSW have not previously been carried out on material with such coarse dendritic or Widmanstätten microstructures. Also, Sonoston has an unusually low thermal diffusivity, and might well behave differently from other materials during FSP.

Experimental Procedure

Sonoston plates (300mm long x 75mm wide x 15mm thick) were machined from a large, slowly cooled casting. Slots and holes of various sizes (up to 10mm long x 5mm deep x 0.5mm wide) were machined in specific locations in several plates to simulate casting porosity (since large, naturally occurring pores were present only in isolated positions). The composition and other properties of the material are given in tables 1 and 2.

Table 1 – Composition (wt %) of Sonoston

Mn	Cu	Al	Fe	Ni	Zn	Si	C	Sn	Pb
54.0	37.45	4.21	2.86	1.21	0.16	0.06	0.02	0.01	0.02

Table 2 – Some Mechanical and Physical Properties of Sonoston [4-6][#]

Young's Modulus [GPa]	Proof Strength [MPa]	Tensile Strength [MPa]	Elongation [%]	Possions Ratio	Fracture Toughness [MPa √m]
73-83	250-315	390-590	2-30	0.33	34±6

Density [kg/m^{-3}]	Damping Capacity [%]	Melting Range [°C]	Thermal Expansion Co-efficient [10^{-6}/°C]	Corrosion Potential [mV versus SCE]	Thermal Diffusivity [$10^{-6}m^2/s$]
7,200	10-30	940-1080	16.5	-700	3.0

[#] Ranges can be broad due to variations in cooling rates and ageing times at ambient temperatures.

FSP was carried out using (i) a cubic boron-nitride (CBN) tool with a pin 7.1mm long, tapered from 9mm to 4.5mm diameter, with three flats around the circumference, and (ii) a Co-Ni-Cr (MP 159) steel tool with a threaded pin 6mm long and 7.5mm diameter. An anti-clockwise rotational speed of 800rpm and translational speeds of 12.7 and 25.4mm/min were used, with the tools inclined 3° from the vertical. Active cooling, via an ice-chilled air blast, was applied during FSP to protect the spindle and to minimise temperature (thermal-expansion) differences between the CBN tool and its metallic housing. For some FSP runs, fine-wire thermocouples were inserted into holes drilled into the blocks, in an attempt to measure local temperatures.

Local FSP temperatures were also estimated by comparing the microstructure of FSP zones with the microstructures of small blocks of Sonoston heated to temperatures in the range 700° to 950°C for various times and cooled in air by placing specimens on large, cold steel blocks, to achieve cooling rates similar to those during FSP. Specimens were also quenched in cold water or furnace-cooled for comparison. Microstructures were characterised by optical microscopy after polishing and etching. Etching involved either swabbing specimens with acidified ferric chloride for several seconds, or anodic polarisation (-200mV versus SCE) in seawater for 15-20 minutes followed by a light re-polish with 1μm diamond paste. More consistent results were obtained using the latter procedure.

Compositional variations across selected microstructural features were measured by wavelength dispersive spectroscopy (WDS). The hardness was also measured in various microstructural zones before and after FSP. Preliminary measurements of residual stresses produced by FSP were made using X-ray diffraction (XRD). Whether residual stresses were high enough to produce SCC was determined simply by immersing specimens in seawater under open-circuit potentials. The corrosion resistance before and after FSP was evaluated using accelerated testing involving immersing specimens in sea water under anodic polarisation (-200mV versus SCE) for up to 24 hours and then sectioning to determine the de-alloying depth.

Results

Initial FSP runs using the CBN tool with a traverse speed of 25.4mm/minute sometimes resulted in a large tunnel defect on the advancing side, presumably due to insufficient flow to completely fill the cavity left in the wake of the tool. Decreasing the traverse speed to 12.7mm/minute consistently resulted in defect-free processed zones for both the CBN and steel tools. Neither the CBN or steel tools performed completely satisfactorily, with the CBN tools having a tendency to fracture and steel tools tending to soften and wear. The surface roughness and the extent of the flash on top of the FSP surface were unacceptably large, but should be able to be reduced by further process and tool development. The surfaces exhibited heat tints, but did not appear to be excessively oxidised. The maximum temperature recorded by the thermocouples placed directly in the path of the CBN and steel pins were 760°C and 775°C, respectively.

Microstructures after FSP. Different zones were apparent both on a macroscopic scale (Fig. 1) and on a microscopic scale (Fig. 2) on transverse sections of plates after a single FSP pass:

(a) Unprocessed zones exhibiting a coarse Mn-rich phase with a dendritic or Widmanstätten morphology in grain interiors, with small Cu_3Mn_2Al particles along grain boundaries.

(b) Heat-affected zones where the original coarse structure was undeformed but more heavily etched than adjacent regions due to fine-scale structural changes.

(c) Mechanically deformed zones where the original coarse structure was bent and elongated, and in more heavily deformed zones, fragmented.

(d) Partially refined zones where there were remnants of the original coarse structure, and a fine Mn-rich phase, with a faceted, plate-like morphology similar to the original structure, between and growing from the coarse structure. Etching (de-alloying) resulted in a network of microcracks in the coarse phase.

(e) Refined zones exhibiting only the fine Mn-rich phase with the faceted, plate-like morphology.

(f) Refined zones exhibiting a very fine equiaxed grain size with relatively equiaxed Mn-rich areas in grain interiors.

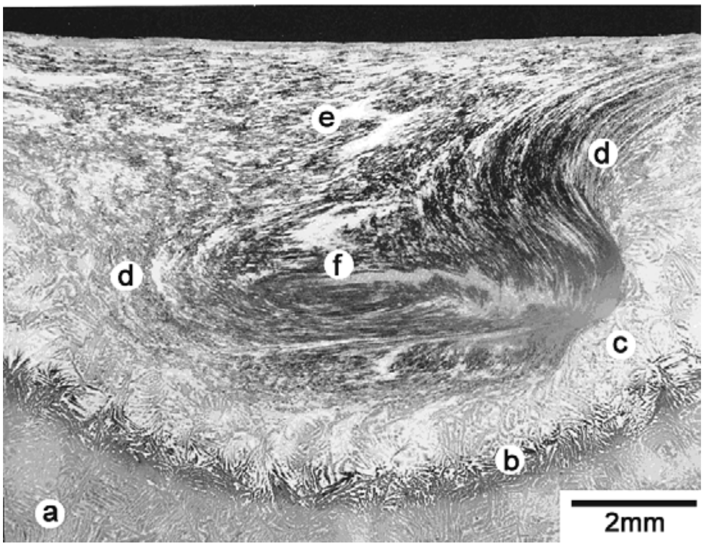

Fig. 1 Optical micrograph of Sonoston after FSP with a CBN tool exhibiting various microstructural zones (labelled (a)-(f) (See text)) shown at higher magnification in figure 2.

The composition of the Mn- rich and Mn-depleted areas appeared to be similar for both the fine and coarse structures, with the Mn-rich areas being about 60%Mn, 29%Cu, 5%Fe, 4%Al, 2%Ni, and the Mn-depleted areas being about 33%Mn, 60%Cu, <1%Fe, 4%Al, 2%Ni. There was little difference in microhardness between the Mn- and Cu-rich areas. The refined zones were somewhat harder (148-159VH) than the unprocessed zones (VH~143). The macroscopic flow patterns were somewhat different for the CBN and steel tools, but all the zones listed above were present in both cases. No signs of the machined slots were evident on longitudinal sections through the FSP zone.

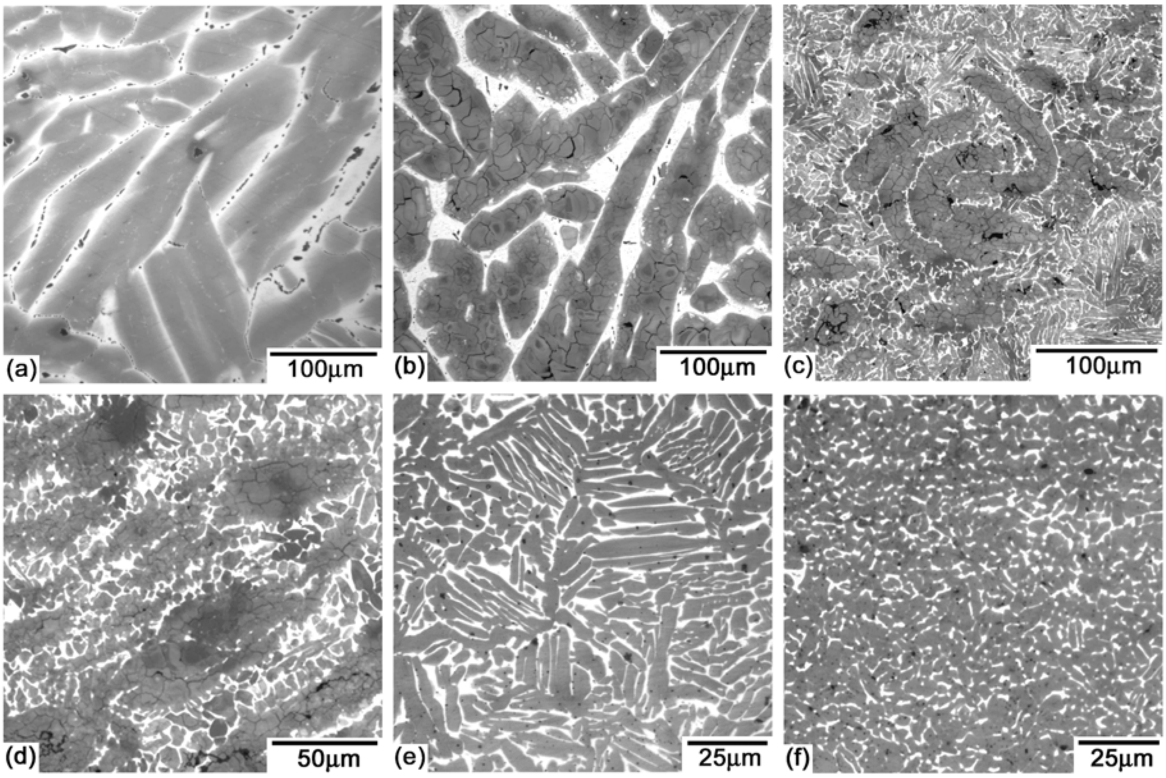

Fig. 2 Optical micrographs showing (a) original cast microstructure, (b) heat-affected zone, (c) mechanically deformed zone, (d) partially refined zone, and (e), (f) refined zones.

Microstructures after Heat Treatments. Small Sonoston blocks heated to temperatures in the range 750°C to 950°C for several minutes and air-cooled exhibited microstructures (Fig. 3) similar to those produced by FSP. Between 800°C and 925°C, mixtures of fine, faceted, plate-like structures and coarse, micro-cracked structures were observed, with the proportion of coarse structure decreasing from about 95% to 5% over this temperature range. After heating to 950°C, only the fine structures were present (Fig. 3(c)). Specimens that were quenched from the above temperatures exhibited what appeared to be a uniform structure at low magnifications, but showed an extremely fine structure similar to air-cooled specimens at high magnifications. Furnace-cooled specimens exhibited coarse structures similar to the original cast structure (Fig. 4).

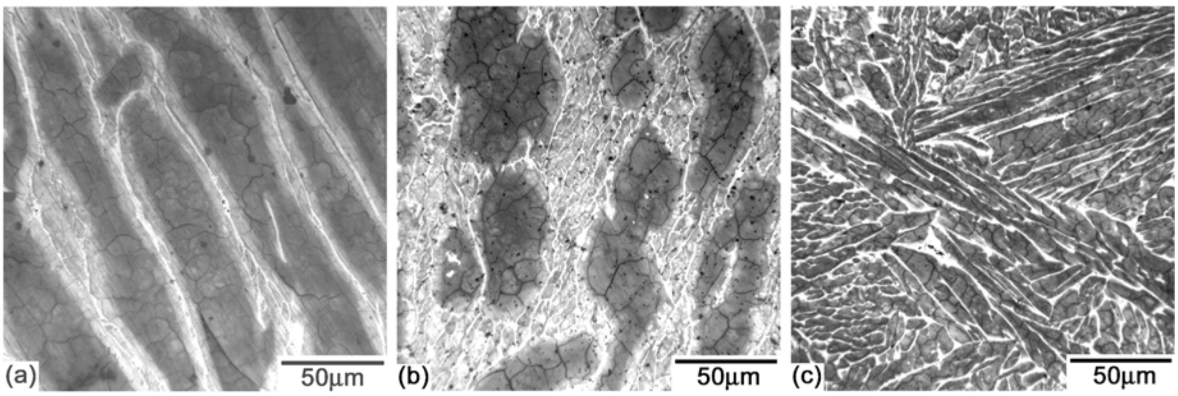

Fig. 3 Optical micrographs showing microstructures of Sonoston after heating to (a) 825°C (b) 850°C, and (c) 950°C, for several minutes, followed by rapid cooling in air.

Residual Stresses. The Sonoston blocks after FSP were bowed in both the transverse and longitudinal directions, indicating that substantial residual stresses had been introduced. XRD measurements showed that tensile residual stresses *very close to the top surface* were low (up to 21MPa) in the FSP zone, and were highest (up to 159MPa) in the parent material adjacent to

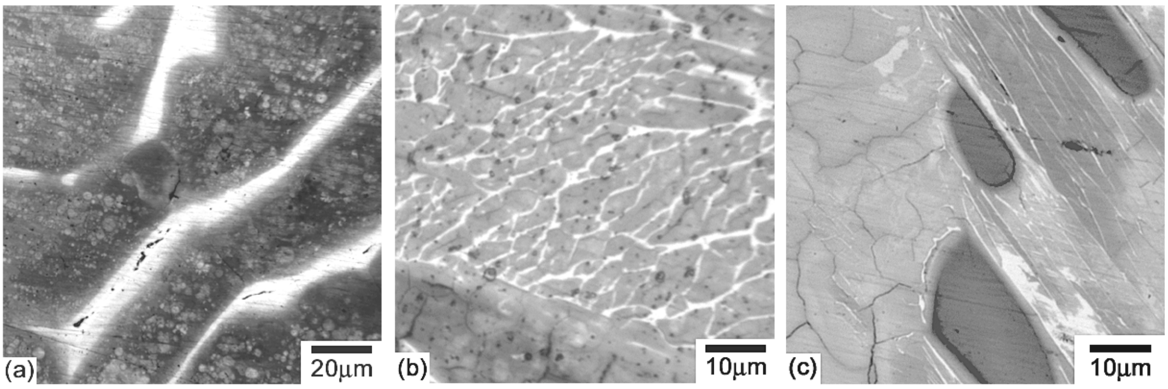

Fig. 4 Optical micrographs showing microstructures after heating to 900°C for several minutes then (a) furnace-cooled, (b) air-cooled, and (c) quenched. (Note lower magnification for (a)).

the FSP zone. Compressive residual stresses (up to 103MPa) were measured in the HAZ. Specimens cut from FSP plates, with ~0.1mm removed from the surface, and exposed without externally applied stresses to sea water (open-circuit potential) exhibited rapid SCC in the FSP zone showing that substantial tensile residual stresses were present just sub-surface. Specimens stress-relieved for various times at temperatures in the range 400°C to 600°C and then exposed to seawater showed that residual stresses could be decreased sufficiently to prevent SCC by heat-treating for 8 h at 500°C whereas 24hrs at 400°C was insufficient.

Corrosion Tests. Accelerated corrosion tests (exposing specimens to seawater at –200mV for various times), showed that the FSP material (not stress-relieved) with the refined microstructure (Fig. 2(e)) was corroded to similar depths as the parent material. In addition, severe cracking and exfoliation occurred for FSP material. In contrast, the depth of the de-alloyed regions for *stress-relieved* FSP material was much less than that for parent material (Fig. 5).

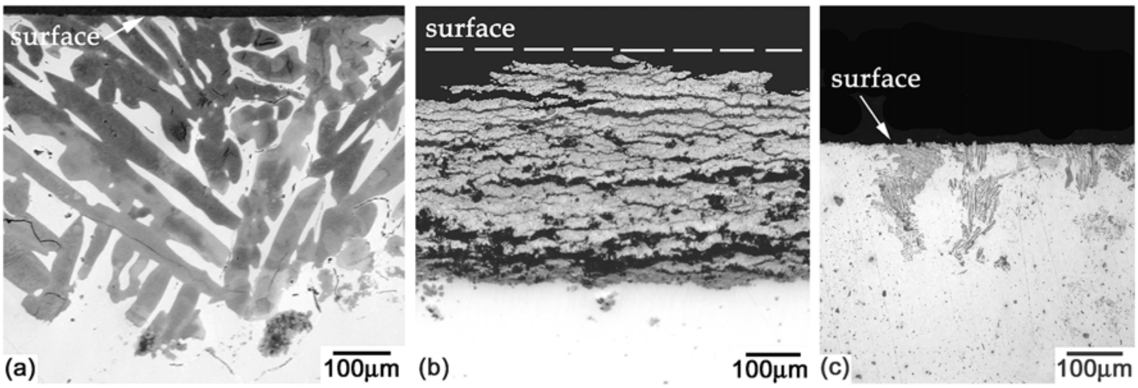

Fig. 5 Optical micrographs of *unetched sections* after corrosion in sea water for 24h at –200mV for (a) parent plate, (b) FSP material, and (c) FSP material given a stress relief at 600°C for 2 h.

Discussion

The refined microstructures produced by FSP (in some areas) are similar to those produced by heating in the range 850 to 950°C followed by rapid cooling in air (but not by slow cooling), e.g. compare figures 2(d) and 3(b). Thus, the refinement by FSP is probably largely due to faster cooling rates from these temperatures after FSP than in the original casting. The refined, faceted plate-like microstructures are produced below the solidus temperature (~940°C) and, hence, they presumably arise from a Widmanstätten phase change. The very fine globular microstructure is probably associated with a fine grain size (produced by dynamic recrystallisation as occurs in other FSP materials) which inhibits the formation of *plate-like* Widmanstätten structures. Widmanstätten microstructures that are more refined by faster cooling rates have been observed in other materials, such as Ti-alloys cooled from the β-phase field to the $\alpha + \beta$ phase field [7].

The details of the phase change that results in a Widmanstätten microstructure in Sonoston are not well established, and previous work on Sonoston [5] does not mention any such phase change. There is also no indication of phase changes occurring in the compositional range of interest between 700 to 940°C from the binary Mn-Cu phase diagram [8]. However, early phase diagrams [9] determined using impure materials (up to 10% Fe+Al+C+Si) (likely to be more relevant to Sonoston) do indicate possible phase transitions.

Comparisons of the FSP microstructures with those of the heat-treated blocks suggest that temperatures close to the solidus temperature occurred during FSP, as occurs in other FSP materials [1-3]. This temperature (~940°C) is well above the maximum temperature of 775°C recorded by thermocouples in the path of the FSP tool. The temperatures recorded by thermocouples showed smooth increases and decreases, suggesting they remained intact during the FSP run. However, the temperatures recorded may have been lower than the maximum temperatures reached in the FSP zone because (i) there was poor contact with the Sonoston or, more likely, (ii) the thermocouples were moved to one side away from the FSP zone as the pin approached.

The refined microstructures resulted in only small increases in strength (based on hardness measurements) probably because there is little difference in hardness between the Mn- rich and Cu-rich phases (and solid-solution hardening dominates over grain size effects). Plate distortion, rapid SCC, and poor corrosion resistance of FSP material were obviously due to high levels of residual stress. Stresses may be higher than in other materials because Sonoston has a very low thermal diffusivity (26 times less than aluminium). The inferior corrosion resistance of FSP material (not stress-relieved) compared with parent material is associated with microcracking and exfoliation driven by high residual stresses. The cracking allows the environment to penetrate to the Mn-rich corrosion-susceptible areas not otherwise connected to the surface, enabling corrosion to continue. The better corrosion resistance of *stress-relieved* FSP material results from the refined structure, with corrosion limited to Mn-rich areas connected to the surface.

The observations that the machined slots and holes (simulating porosity) were eliminated by FSP are not surprising considering that extreme deformation is involved in the process, and that the technology is used for joining materials. However, stress-relieving a large propeller casting at 500°C to relieve residual stresses may not be feasible without resultant distortions. Thus, further work to try to optimise FSP parameters to produce a refined microstructure with much lower residual stresses (and better surface finish) is required.

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